26. Motion Cues in Man-Vehicle Control*

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The human operator's use of roll-angular-motion cues in man-vehicle control is investigated. Extensive data for the human operator's describing function and remnant are taken for a wide range of vehicle dynamics under conditions of visual cues only, roll-motion cues only, and simultaneous visual and roll-motion cues. Addition of roll-motion cues to visual cues permits the human operator to increase his phase lead at frequencies above 2 rad/sec, thereby allowing higher gain and crossover frequency and reduced tracking error.

INTRODUCTION

If a man is to be in the control loop of a proposed vehicle, it is necessary to consider his control characteristics from the outset of the vehicle design. In the past, this problem has generally led to the simulation of the proposed vehicle dynamics on an analog computer and the testing of the pilot's ability to control the simulated dynamics in the laboratory. Unfortunately, the results of such fixed-base experiments did not always agree with later experiments performed with the actual aircraft. To obtain the correct results in the laboratory, additional simulations of the proposed vehicle's cab, sounds, and motions were made. It was learned that in many cases the simulation of vehicle angular motions was of primary importance. When the vehicle angular motions were simulated in the laboratory, laboratory data were often in close agreement with later flight data. Young (ref. 1) attributed this to the fact that angular-motion cues frequently are used to stabilize vehicle orientation prior to controlling vehicle position and, thus, become of primary importance. For example, before stabilization of the lateral position of a hovering helicopter, it is necessary to stabilize its roll angle.

Because motion simulation is difficult and expensive, as is the use of variable-stability aircraft, it would be useful to be able to predict actual in-flight data for the human operator from laboratory fixed-base experiments. The results presented in this paper, which concern the human operator's use of roll motion cues, represent a step in this direction.

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THE EXPERIMENT

The following experiment was performed to obtain data for the human operator to determine how he uses roll-motion cues in vehicle control. Data were taken while the human operator was presented visual cues only, roll-motion cues only, and simultaneous visual and roll-motion cues. Data were also taken for a wide range of vehicle dynamics, and for a range of other experimental parameters. The vehicle dynamics tested included

$$Y_c(s) = \frac{K}{s(\tau s+1)} \quad , \text{ K and } \tau \text{ vary} \tag{1}$$

$$Y_c(s) = \frac{\omega_n^2}{s^2+2\xi\omega_n s+\omega_n^2} \quad , \omega_n^2 \text{ and } 2\xi\omega_n \text{ vary} \tag{2}$$

$$Y_c(s) = \frac{\omega_n^2}{s(s^2+2\xi\omega_n s+\omega_n^2)} \quad , \omega_n^2 \text{ and } 2\xi\omega_n \text{ vary} \tag{3}$$

where s is the Laplace operator. The dynamics given by equations (1) through (3) are of general interest. For example, among other things equation (1) corresponds to simplified airplane lateral dynamics (for various values of K and τ), relating aileron angle to roll angle. Similarly, equation (3) corresponds to some compensated helicopter dynamics (with roll-angle feedback), relating control-stick position to horizontal position. The other experimental parameters which were varied (one at a time) include control-stick gain, system input power, and the input-spectrum breakpoint.[1]

Subjects were placed in the cab of a simulator capable of producing roll motions, and the vehicle dynamics were simulated on an analog computer. The subjects' bodies were tightly strapped in place, but their heads were not directly restrained. The cab of the simulator was covered, and contained an oscilloscope and a control stick. The system attitude error was displayed to the man as a horizontal displacement of a dot from the centered position on the oscilloscope face (for visual cues), and as a rotation in roll of the simulator cab from the vertical (motion cues). The dynamics of the simulator were nearly equal to a pure delay of 0.1 second ($e^{-\cdot 1s}$) over the frequency range of interest (0.1 to 10 rad/sec). To make the visual and motion cues correspond to each other, a 0.1-second delay was placed in the visual loop. All the simulations of vehicle dynamics included this delay. As shown in figures 1 and 2, the subjects were in a compensatory system. They had the task of processing visual and roll-motion cues of system error, along with their knowledge of the vehicle dynamics, to manipulate the control stick so as to stabilize and control the man-vehicle system.

Paralleling the work of McRuer et al. (ref. 2), data were taken during 89.6-second runs: the human operator's input and output were sampled every 0.1 second. The data taken were of display and control-stick voltages which were scaled so as to be directly comparable. The data were processed in the same manner as by McRuer et al., except that a hybrid computer was used instead of watt-hour meters. The actual calculations performed (excepting further calculations to correct for the remnant) were

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[1]The system input was the sum of 10 sinusoids. The higher frequency sines were reduced in amplitude to one-tenth the amplitude of the lower frequency sines. The frequency at which the reduction in amplitude occurs is called the input breakpoint. See references 2 and 3.

$$|Y_p(\omega_k)| \doteq \frac{|M_m(\omega_k)|}{|e(\omega_k)|}$$ amplitude ratio of the human operators describing function (4)

$$\angle Y_p(\omega_k) = \angle M_m(\omega_k) - \angle e(\omega_k)$$ phase of the human operators describing function (5)

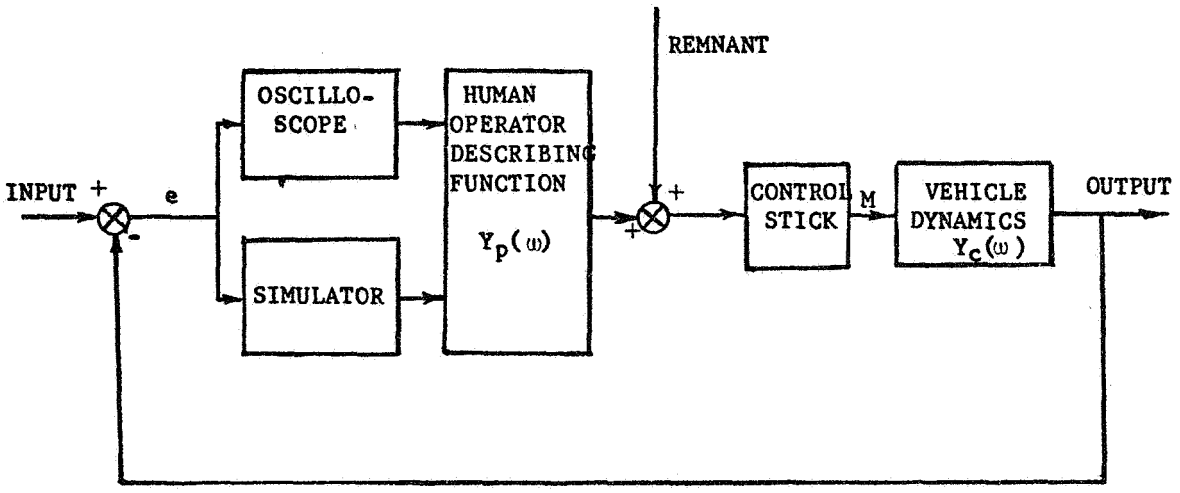

Figure 1.—The human operator in a compensatory system.

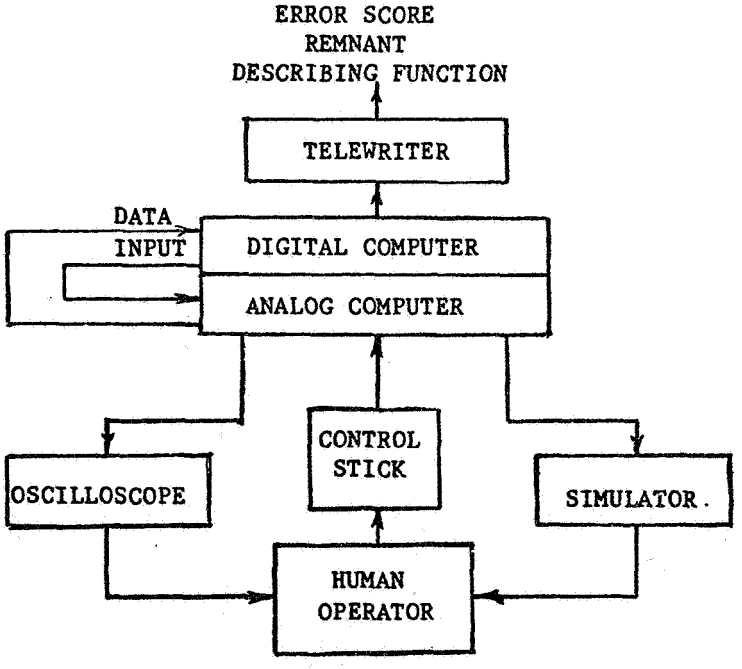

Figure 2.—The experimental set-up.

where

$$\left|M_m(\omega_k)\right|^2 = (A_{mk}^2 + B_{mk}^2)(\Delta t)^2 \qquad \angle M_m(\omega_k) = \tan^{-1}\left(\frac{B_{mk}}{A_{mk}}\right)$$

$$\left|e(\omega_k)\right|^2 = (A_{ek}^2 + B_{ek}^2)(\Delta t)^2 \qquad \angle e(\omega_k) = \tan^{-1}\left(\frac{B_{ek}}{A_{ek}}\right)$$

where

$$A_{mk} = \sum_{n=1}^{896} M(n\Delta t)\sin(\omega_k n\Delta t) \qquad A_{ek} = \sum_{n=1}^{896} e(n\Delta t)\sin(\omega_k n\Delta t)$$

$$B_{mk} = \sum_{n=1}^{896} M(n\Delta t)\sin(\omega_k n\Delta t) \qquad B_{ek} = \sum_{n=1}^{896} e(n\Delta t)\cos(\omega_k n\Delta t)$$

where $e(n\Delta t)$ and $M(n\Delta t)$ are the sampled values of the man's input and output as shown in figure 1. The system input was the sum of 10 sinusoids of known amplitude, frequency (the ω_k's), and phase in a "shelf" spectrum. See reference 3 for further details of the experiment as well as a complete presentation of the experimental data.

Figure 3 shows typical experimental results for one set of vehicle dynamics, namely for

$$Y_c(s) = \frac{e^{-.1s}}{s}$$

The data include the human operator's describing function (amplitude ratio and phase versus frequency), the human operator's remnant (power spectral density of that portion of the human operator's output which is uncorrelated with his input), and system relative integral squared error (the ratio of the average input power during the runs), all for conditions of visual cues only, roll-motion cues only, and simultaneous visual and roll-motion cues.

THE REMNANT CORRECTION

There has been some controversy as to how the measurements of the human operator's describing function are affected by the remnant. Some claim that in calculating the human operator's describing function, using the cross-correlation functions between the system input and the human operator's input and between the system input and the human operator's output, the effects of the remnant are eliminated. Unfortunately this is not completely true: the cross-correlation technique tends to reduce the effect of the remnant on the measurements,

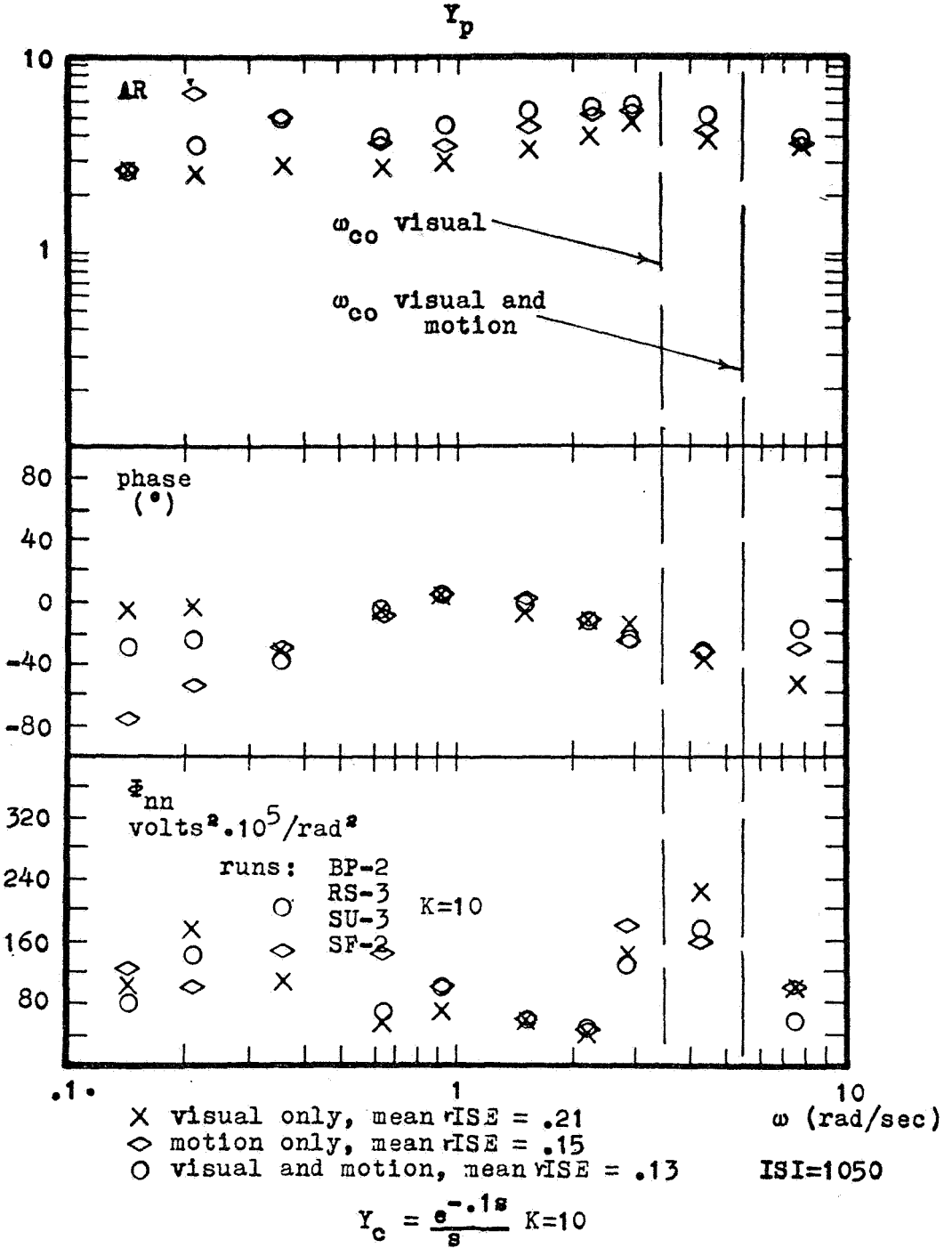

Figure 3.—Experimental results.

but does not eliminate it. Because data are taken for a finite run time, all the measurements have a finite bandwidth, and some remnant enters into all the calculations. The pertinent question, then, is not whether the remnant affects the measurements of the human operator's describing function, but rather how much the remnant affects the measurements. In reference 3 an analytical expression for the effects of the remnant on the experimental measurements of the human operator's describing function was derived. The expression permitted correction of the data for the effects of the remnant as shown in figure 4. As can be seen, the effects of the remnant are small compared to one standard deviation of the data and hence may be ignored. This held true for all the data obtained.

RESULTS

The data were fitted with models of the type

$$Y_p(s) = \frac{Ke^{-\tau_d s}(\tau_1 s+1)(\tau_2 s+1)}{(\tau_3 s+1)(\tau_4 s+1)(\tau_5 s+1)} \tag{6}$$

or of the type

$$Y_p(s) = \frac{Ke^{-\tau_d s}(\tau_1 s+1)(s^2+2\xi\omega_n s+\omega_n^2)}{\omega_n^2(\tau_2 s+1)(\tau_3 s+1)} \tag{7}$$

A brief discussion of these models is given in reference 3. The model given by equation (6) is developed in reference 2. Examination of the values of the model parameters at each point for which data were taken, as well as direct examination of the data, leads to the following conclusions about the human operator's use of roll-motion cues in man-vehicle control. As shown schematically in figure 5, when roll-motion cues are added to visual cues, the human operator increases his phase lead at the higher frequencies (generally above 2 rad/sec). This in turn permits him to increase his gain, and hence his crossover frequency,[2] without a loss in phase margin. These changes in the human operator's describing function occur very consistently throughout the data as shown in table 1.

Since roll-motion cues are of help to the human operator primarily at the higher frequencies, one would expect motion cues to be most beneficial for vehicle dynamics which lead to more high-frequency motions (motions above 2 rad/sec). Figures 6 through 8 show that such is the case. In figures 6 and 7 we see that low-order vehicle dynamics, which pass more high-frequency signals, permit the human operator to make greater use of roll-motion cues when these roll-motion cues are added to visual cues. "Greater use" is measured as the percent improvement in the integral squared error during a run, when the roll-motion cues are added to the visual cues. Furthermore, figure 6 shows that for vehicle dynamics with a high control-stick gain, which permits the human operator to force the vehicle to make rapid responses, the human operator can make more use of roll-motion cues than for the same vehicle with a lower control-stick gain. Finally, figure 8 shows that without exception (in the range of vehicle dynamics studied), the addition of a pole at the origin to a second order system leads to the human operator being less able to utilize roll-motion cues.

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[2]The crossover frequency is that frequency at which the open loop gain (the product of the magnitudes of the human operator's describing function and the vehicle dynamics) passes from greater than unity to less than unity.

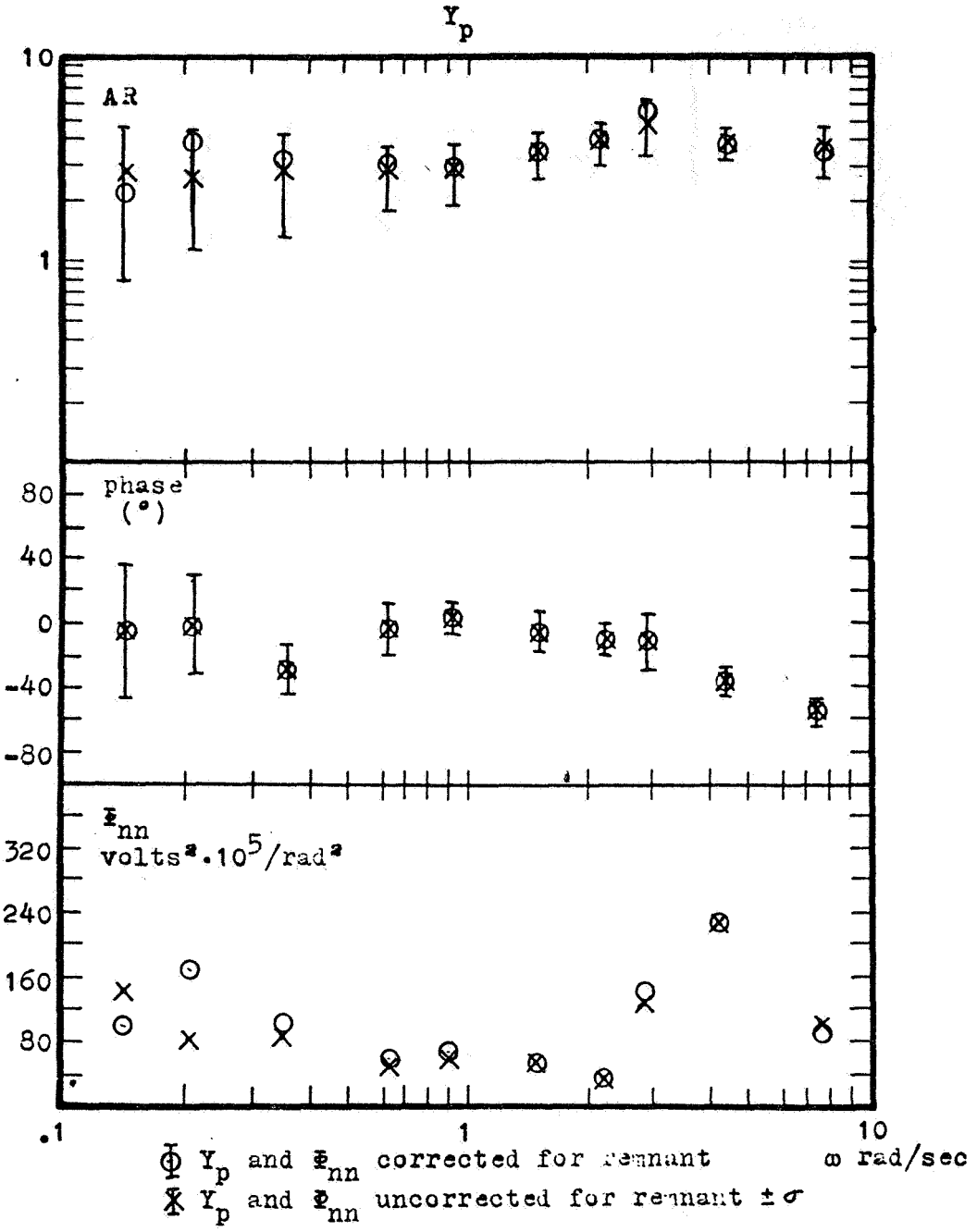


Figure 4.—The effect of the remnant correction to Y_p for $Y_c=e^{-.1s}/s$.

It should be remembered that these results are not based on a comparison of error scores, but on a comparison of percentage improvements in error scores when roll-motion cues are added to visual cues. It is interesting to note that at no point did the addition of roll-motion cues actually degrade performance, although there were dynamics for which motion cues were of no help to the human operator, such as for

$$Y_c(s) = \frac{2e^{-.1s}}{s^2(s+2)}$$

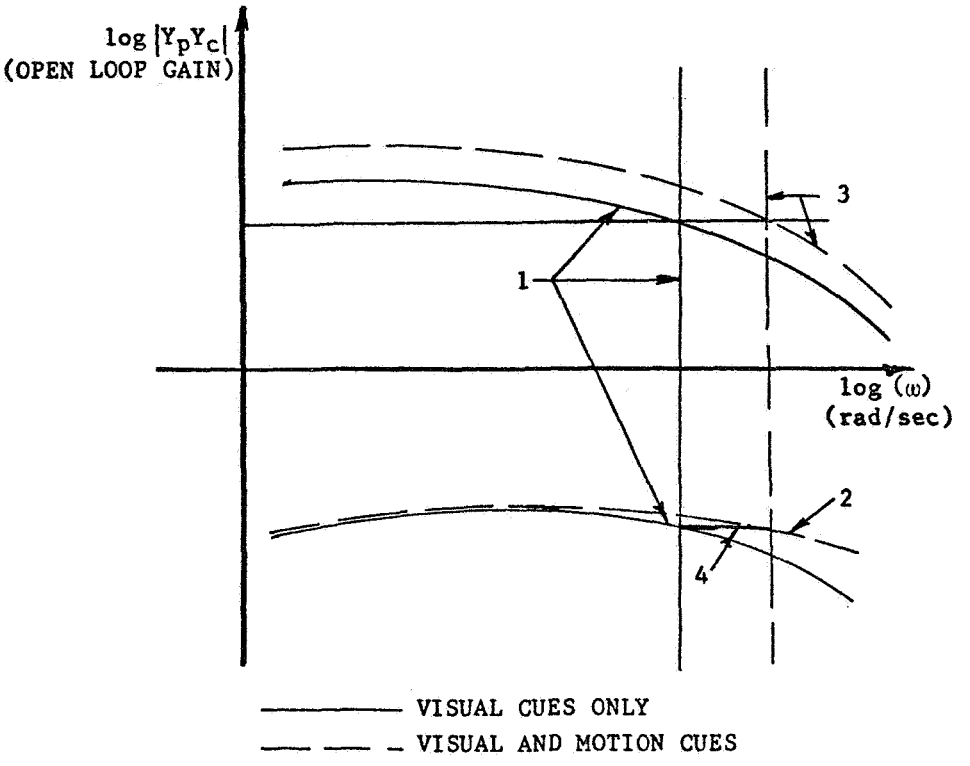
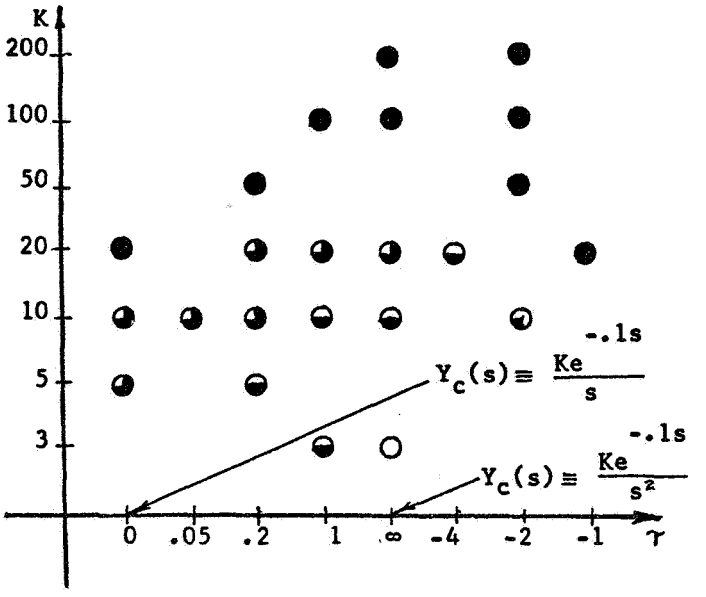


Figure 5.—How the human operator changes his control behavior upon the introduction of roll motion cues. (1) While controlling a vehicle with visual cues only, the human operator-plant combination has a certain amplitude ratio, phase, and cross-over frequency. (2) The addition of roll motion cues to visual cues of system error permits the human to generate more lead at the higher frequencies. (3) Thus he can increase the system gain (and the cross-over frequency). (4) Without a loss in phase margin.

It should also be noted that figure 8 confirms the finding of reference 1 that motion cues help most for unstable vehicle dynamics which are near the limits of controllability.

SUMMARY

The objective of this investigation was to learn about the human operator's use of roll-motion cues and, thus, to take a step in the direction of predicting actual flight data for the human operator from fixed-base laboratory experiments. In reference 4, Meiry has shown that the vestibular dynamics are very similar in pitch and roll. Thus it would seem appropriate to assume that the results obtained with roll-motion cues are similar to, if not the same as, the results which would be obtained if pitch-motion cues were used. Therefore, we can say that when the differences between fixed-base laboratory data and flight data for the human operator are due to the absence of pitch- and roll-motion cues in the



KEY: (figures 7 and 8)

○ MOTION CUES ARE NEUTRAL

● MOTION CUES ARE EXTREMELY HELPFUL

Figure 6.—The effects of motion cues on the performance of the man-vehicle system for the vehicle dynamics $Y_c(s) = \frac{Ke^{-.1s}}{s(\tau s + 1)}$.

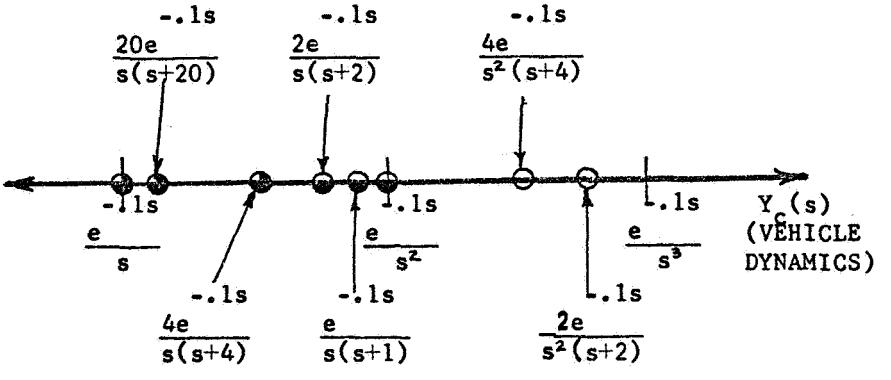


Figure 7.—The effects of motion cues on the performance of the man-vehicle system as the vehicle dynamics range from $e^{-.1s}/s$ to $e^{-.1s}/s^3$.

laboratory, the data given in reference 3 permit prediction of flight data from fixed-base laboratory data for the human operator. These predictions are quantitative, and not merely qualitative in nature. They are, however, restricted to vehicle dynamics for which data were taken, namely equations (1) through (3). It is possible to estimate results for vehicle dynamics of the types

$$Y_c(s) = \frac{(1+Cs)}{s^2} \tag{8}$$

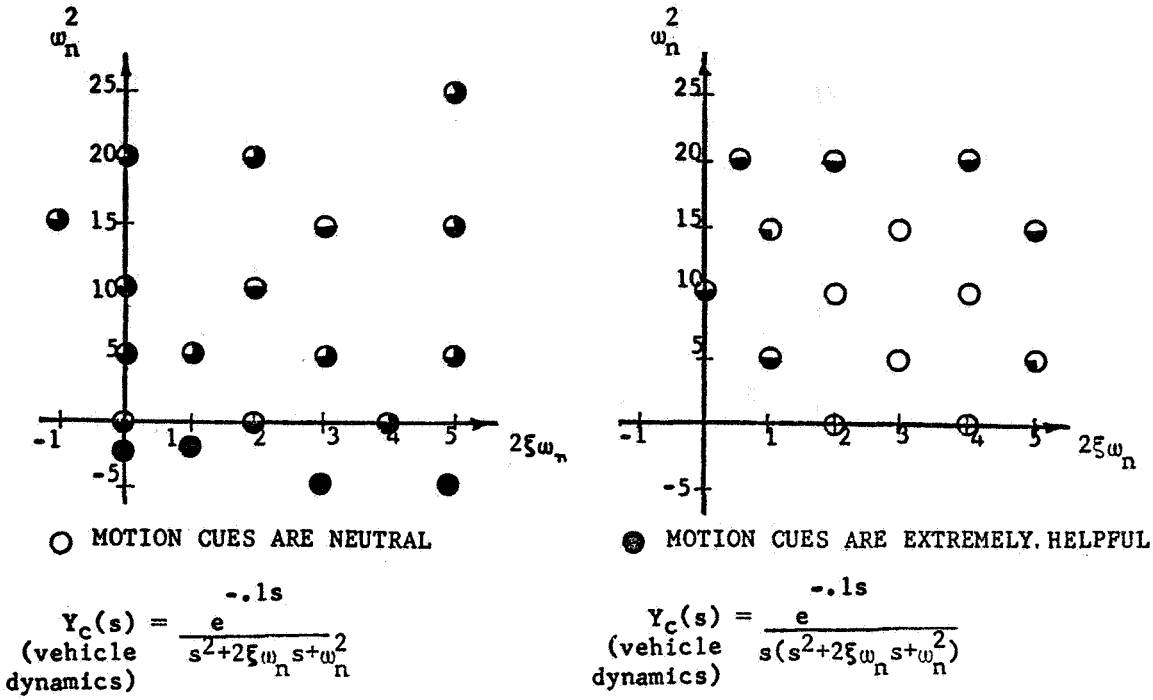


Figure 8.—The effects of motion cues on the man-vehicle system for various vehicle dynamics.

and

$$Y_c(s) = \frac{(1+Cs)}{s(s^2+2\xi\omega_n s+\omega_n^2)} \tag{9}$$

by interpolating between results for which data were taken.[3]

While the results presented here should be very useful, much remains to be done. At present, experiments are underway at MIT to learn how the human operator uses yaw-motion cues, and at NASA-ERC to measure the human operator's describing function over a wider range of dynamics. Experiments are planned to study the human operator's use of translational motion cues. Finally, a physiologically based model of the human's use of motion cues, using our knowledge of vestibular dynamics, remains to be developed.

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[3]For example, data were taken for the vehicle dynamics $Y_c(s) = e^{-.1s}/s$ and $Y_c(s) = e^{-.1s}/s$ (eq. (2)). As C varies from ∞ to 0 equation 8 varies from $Ke^{-.1s}/s$ to $Ke^{-.1s}/s^2$, between the two points for which data were taken.

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